United States Patent [19]

Zinger et al.

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[45] **Date of Patent: Dec. 9, 1986**

[54] **MULTIPORT RECTANGULAR TE_{10} TO CIRCULAR TE_{01} MODE TRANSDUCER HAVING PYRIMIDAL SHAPED TRANSDUCING MEANS**

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[73] Assignee: **The Johns Hopkins University,** Baltimore, Md.

[21] Appl. No.: **532,892**

[22] Filed: **Sep. 16, 1983**

[51] **Int. Cl.**[4] **H01P 1/16**

[52] **U.S. Cl.** .... **333/137**; 333/21 R

[58] **Field of Search** .... 333/21 R, 21 A, 137, 333/136, 34, 248, 239, 251, 245

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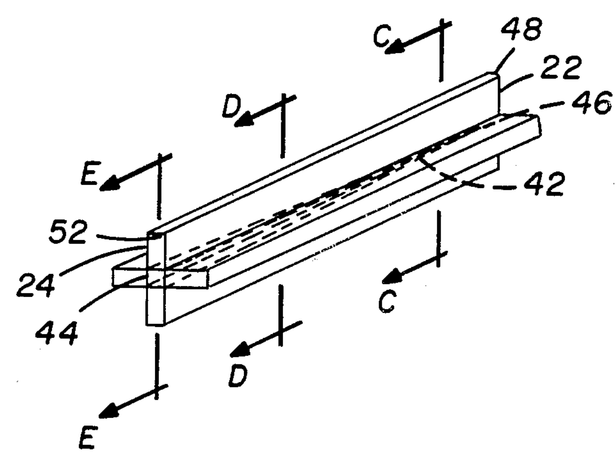
Primary Examiner—Paul Gensler
Assistant Examiner—Benny T. Lee
Attorney, Agent, or Firm—Robert E. Archibald

[57] **ABSTRACT**

A method and device for transducing multiple rectangular TE_{10} modes to circular TE_{01} mode. Multiple TE_{10} modes are transitioned into an intermediate mode which is transitioned into a circular TE_{01} mode and vice versa. Unique pyramidal structure provides overmoded high power operation without cooling and/or pressurization.

6 Claims, 24 Drawing Figures



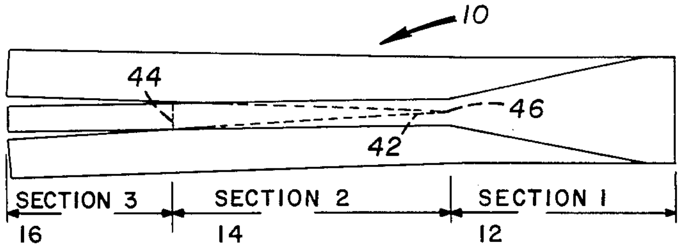


FIG. 1

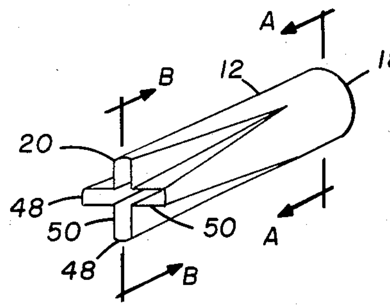


FIG. 2

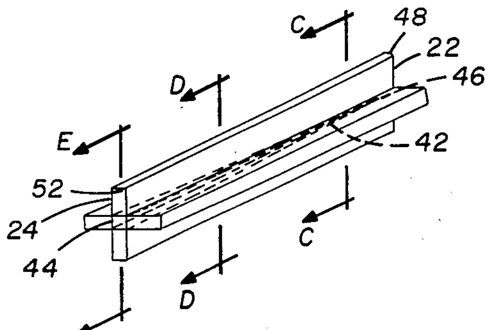


FIG. 3

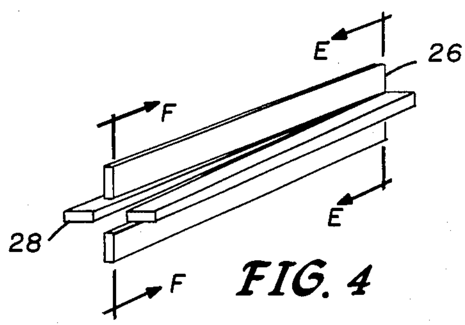


FIG. 4

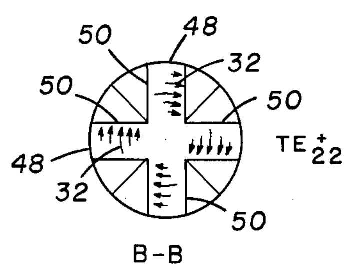


FIG. 6

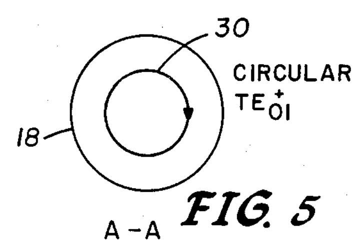


FIG. 5

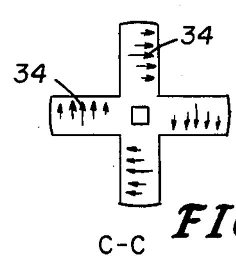


FIG. 7

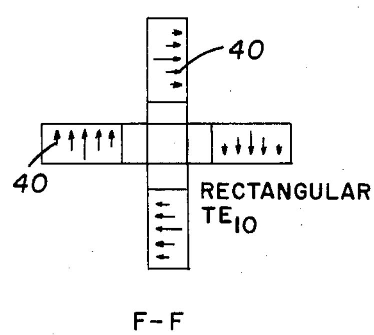


FIG. 10

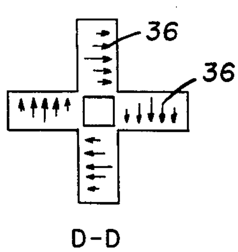


FIG. 8

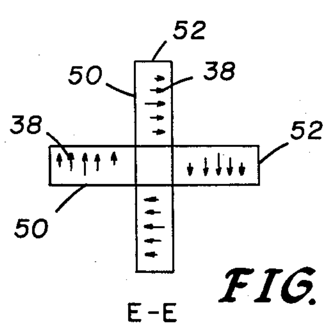


FIG. 9

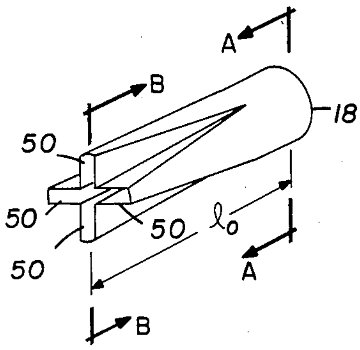


FIG. 11

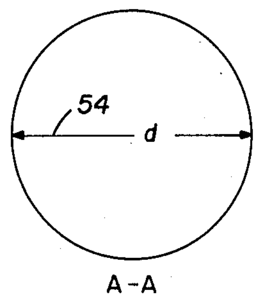


FIG. 12

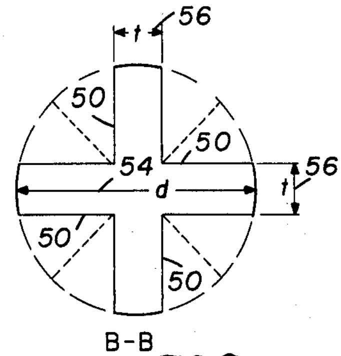


FIG. 13

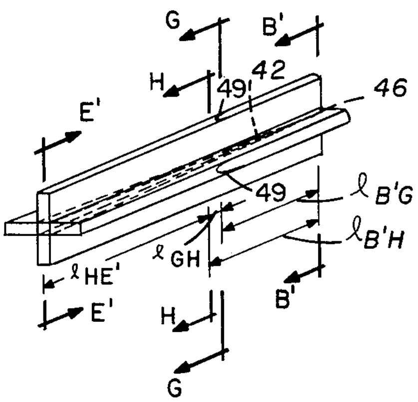


FIG. 14

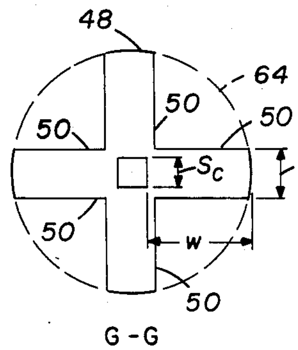


FIG. 16

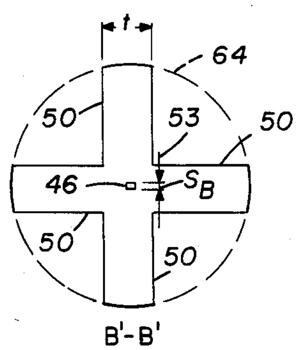


FIG. 15

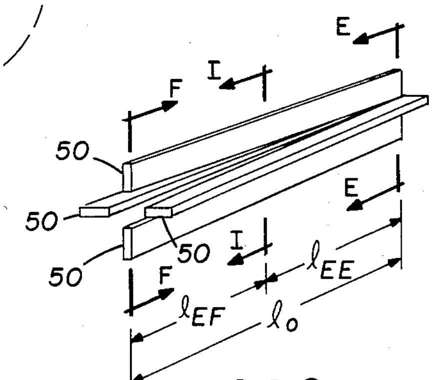


FIG. 19

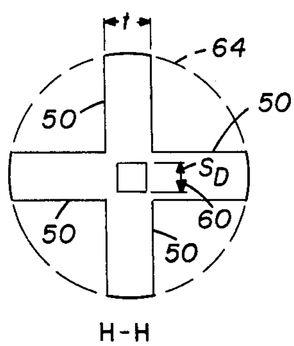


FIG. 17

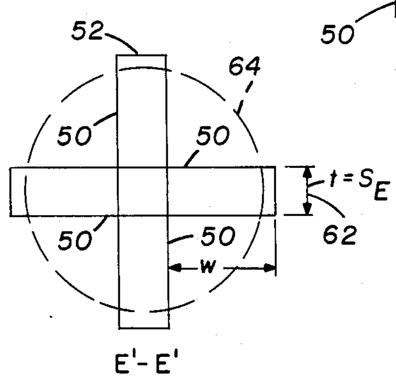


FIG. 18

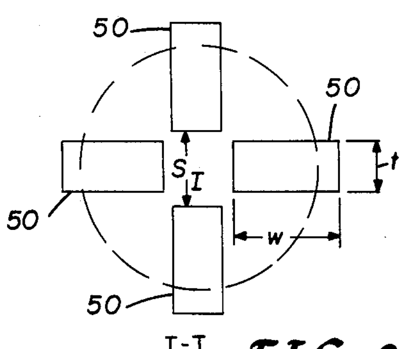


FIG. 20

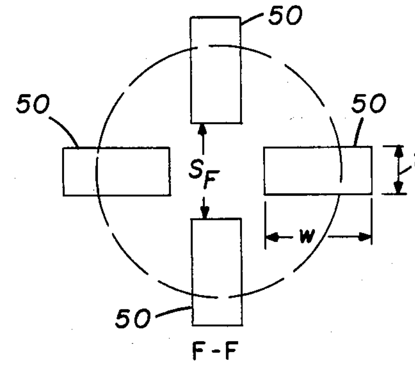


FIG. 21

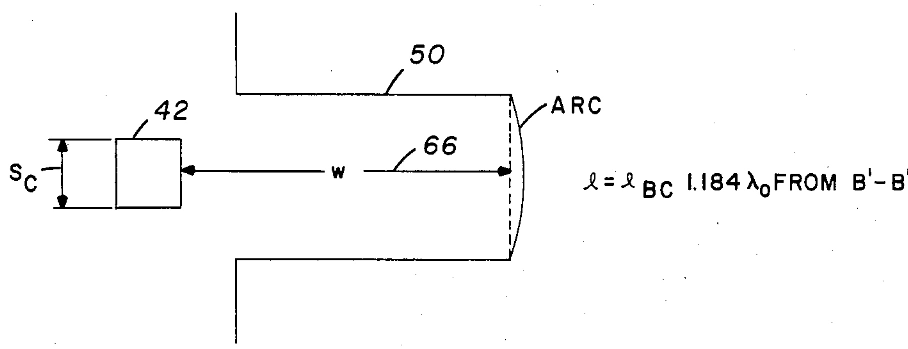


FIG. 22

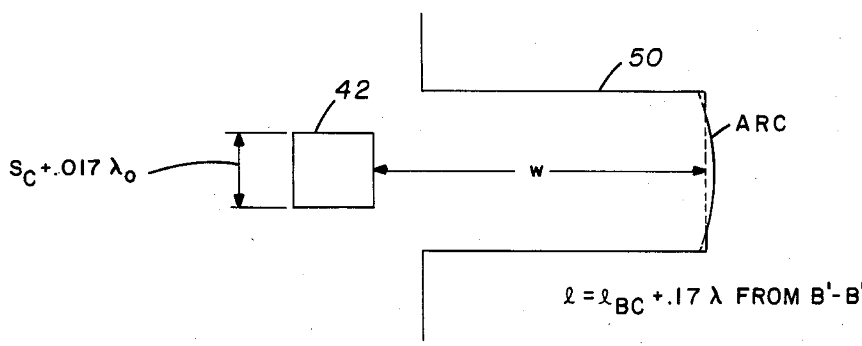


FIG. 23

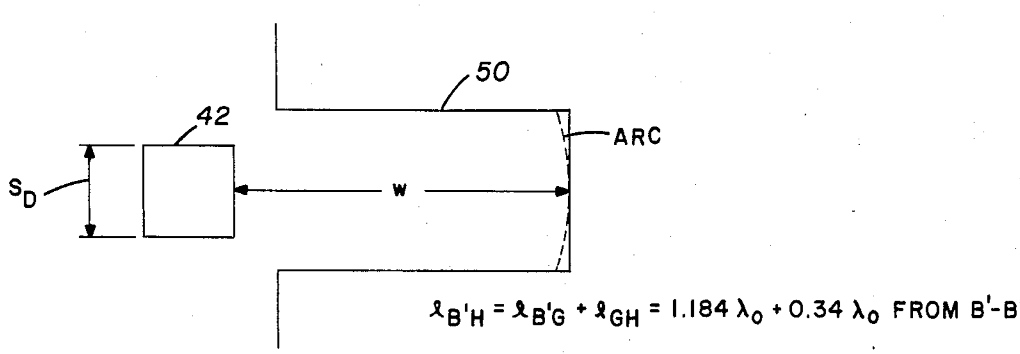


FIG. 24

MULTIPORT RECTANGULAR TE_{10} TO CIRCULAR TE_{01} MODE TRANSDUCER HAVING PYRIMIDAL SHAPED TRANSDUCING MEANS

STATEMENT OF GOVERNMENTAL INTEREST

The Government has rights in this invention pursuant to Contract No. N00024-81-C-5301 awarded by the Department of the Navy.

BACKGROUND OF THE INVENTION

This invention relates generally to overmoded waveguides and more particularly to a multiport rectangular TE_{10} to circular TE_{01} mode transducer.

Waveguides can generally be classified as "fundamental mode" or "overmoded". A fundamental mode waveguide is designed with dimensions which support only the fundamental electromagnetic field, or mode, configuration for propagation in a given frequency band. An overmoded waveguide is designed so that several or many modes can be supported with internal structures to suppress all but the desired modal configuration. In practice, the fundamental mode waveguide, also known as the "standard" waveguide, is far more common as it is more easily designed and constructed. However, the standard waveguide is severely restricted in maximum power capacity and in minimum loss because of its required cross sectional dimensions. The advantages of an overmoded waveguide are that it can be designed to have arbitrarily high power capacity and arbitrarily low attenuation by appropriately increasing the cross section. Required suppression of unwanted modes is achieved using dielectric and metallic structures to restrict allowable modes, see "Trunk Waveguide Communication," A. E. Karbowiak, Chapman and Hall, LTD, London, 1965.

Overmoded waveguides have been utilized as telecommunications trunk transmission lines and to connect transmitters to communications or radar antennas, see "WT4 Millimeter Waveguide System: Introduction," W. D. Waters, Bell System Technical Journal, Vol. 56, No. 10, Dec. 1977, pp. 1825–1827 and "Practical Aspects of High Power Circular Waveguide Systems," R. M. Collins, NEREM Record 1962, pp. 182–183. The most common type of overmoded waveguide supports the circular TE_{01} mode which has the unique property of decreasing transmission loss with increasing frequency for a given diameter, see "Trunk Waveguide Communication," A. E. Karbowiak, Chapman and Hall, LTD, London, 1965. Although applied most often to exploit the low-loss characteristic, the potential for overmoded waveguides to support higher power than standard waveguides has also been considered, see "On the Feasibility of Power Transmission Using Microwave Energy in Circular Waveguide," W. Lowenstein, Jr. and D. A. Dunn, The Journal of Microwave Power Symposium Proceedings, Part B, Vol. 1, No. 2, 1966, pp. 57–61.

Energy is generally supplied to or extracted from the desired mode in an overmoded waveguide from or by a standard waveguide via a "mode transducer". Several such mode transducers efficiently couple microwave or millimeter wavelength energy between a standard rectangular cross section waveguide TE_{10} mode and the overmoded circular cross section waveguide TE_{01} mode. One type of transducer involves direct transition from one mode to another through a region of gradually varying waveguide cross section. U.S. Pat. Nos. 2,859,412 to Marie, 2,779,923 to Purcell and 3,349,346 to Enderly teach this type of transducer which is generally efficient over a relatively wide frequency band.

Another type of rectangular TE_{10} to circular TE_{01} mode transducer is formed by providing a common wall between the rectangular and circular waveguides with modal coupling provided through holes or slots of specific separation in the common wall. Such transducers, including those taught in U.S. Pat. Nos. 2,848,690 to Miller, 3,918,010 to Marchalot and 3,369,197 to Giger, et al. provide efficient energy transfer over a more restricted bandwidth than the first type of transducer because of the particular spacing of the holes or slots relative to a guide wavelength. This bandwidth restriction can be alleviated by using special structures within the transducer, as taught by U.S. Pat. No. 2,948,864 to Miller.

Since the peak power carrying capacity of standard waveguides is generally lower than that of overmoded waveguides, the above transducers do not allow transfer of power to or from the overmoded waveguides at a level which the overmoded components are capable of supporting without substantial pressurization and cooling of the standard waveguide sections. Pressurization and temperature control are conventional methods of increasing standard waveguide power capacity, however, there are practical constraints to these methods.

The present invention teaches a device to appropriately connect multiple standard waveguides to an overmoded waveguide to increase transducer power capacity via division of power among the standard components. The U.S. Pat. No. 3,369,197 to Giger et al. teaches multiple waveguide feeds which are designed to couple to different overmoded waveguide modes or to different frequency channels but not to transfer maximum power. The present invention couples part of the geometry from the Marie transducer, U.S. Pat. No. 2,859,412 to a new section to provide a new transducer which divides power in the overmoded TE_{01} mode equally among several standard rectangular waveguides consistent with the standard waveguide's power capacities. This allows efficient coupling over a relatively wide bandwidth between the circular TE_{01} mode overmoded waveguide and a multiple of standard rectangular TE_{10} mode waveguides without requiring pressurization. The power capacity of the transducer taught by the present invention can be increased by simply increasing the diameter of the overmoded waveguide and increasing the number of standard rectangular waveguides feeding the transducer.

It is therefore one object of this invention to provide a multiport rectangular TE_{10} to circular TE_{01} mode transducer.

It is another object of this invention to provide a multiport rectangular TE_{10} to circular TE_{01} mode transducer for overmoded waveguides.

It is a further object of this invention to provide a multiport rectangular TE_{10} to circular TE_{01} mode transducer for overmoded waveguides that is capable of handling high power.

It is still another object of this invention to provide a multiport rectangular TE_{10} to circular TE_{01} mode transducer for overmoded waveguides that is capable of handling high power without requiring pressurization or cooling.

Other objects, advantages and novel features of the present invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings.

SUMMARY OF THE INVENTION

These and other objects, features and advantages of the invention are accomplished by providing a method and device for transducing multiple rectangular TE_{10} modes to a circular TE_{01} mode and conversely for transducing a circular TE_{01} mode to multiple TE_{10} modes. A first section of the device provides or extracts multiple rectangular TE_{10} modes, a second section transitions the TE_{10} modes to or from an intermediate mode and a third section transitions the intermediate mode to or from a circular TE_{01} mode. A unique pyramidal structure in the second section provides for the transitioning of the rectangular modes to or from the intermediate mode.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and further objects and novel features of the present invention will more fully appear from the following description when the same is read in connection with the accompanying drawings. It is to be understood, however, that the drawings are for the purpose of illustration only, and are not intended as a definition of the limits of the invention.

FIG. 1 is a plan view of the device as taught by the present invention shown divided into three sections.

FIG. 2 shows section 1 of the present invention.

FIG. 3 shows section 2 of the present invention.

FIG. 4 shows section 3 of the present invention.

FIGS. 5 and 6 show sections AA and BB illustrated in FIG. 2.

FIGS. 7 and 8 show sections CC and DD illustrated in FIG. 3.

FIG. 9 shows section EE illustrated in FIGS. 3 and 4.

FIG. 10 shows section FF illustrated in FIG. 4.

FIG. 11 shows section 1 of the present invention.

FIGS. 12 and 13 show section AA and BB illustrated in FIG. 11.

FIG. 14 shows section 2 of the present invention.

FIGS. 15–18 show sections B'B', GG, HH and E'E' illustrated in FIG. 14.

FIG. 19 shows section 3 of the present invention.

FIGS. 20 and 21 show sections II and FF illustrated in FIG. 19.

FIGS. 22–24 show dimensional details of section 2.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The following description of the preferred embodiment describes a four-port rectangular TE_{10} to circular TE_{01} mode transducer. It is to be clearly understood, however, that this invention comprehends an n-port device.

Referring now to the drawings, FIG. 1 is a plan view of a four-port rectangular TE_{10} to circular TE_{01} mode transducer **10**. Transducer **10** is shown divided into sections **1**, **2** and **3**, indicated at **12**, **14** and **16** respectively and is done for purposes of illustration only. FIG. 2 shows section **1** with a cylindrical end **18** and an end **20** wherein the cylinder has been divided into four arms. It is noted that the number of arms is equal to n, the number of ports. FIG. 3 shows section **2** with an end **22** corresponding to end **20** of section **1** and a second end **24**. FIG. 4 shows section **3** with one end **26** corresponding to end **24** of section **2** and an end **28**. End **18** of section **1** is connected to a circular waveguide, not shown, and end **28** is connected to four individual rectangular waveguides, not shown. FIG. **5** shows section AA of FIG. **2** and arrow **30** indicates the electric field pattern. The direction of the arrows indicating the electric field pattern indicates relative polarizations and the length of the arrows indicates relative electric field strength. FIG. **6** shows section BB of FIG. **2** and arrows **32** indicate the electric field patterns. FIG. **7** shows section CC of FIG. **3** and arrows **34** indicate the electric field patterns. Similarly FIGS. **8**, **9** and **10** show sections DD and EE of FIGS. **3** and **4** and arrows **36**, **38** and **40** indicate electric field patterns present at each section.

Section **1**, shown in FIG. **2**, transforms the circular TE_{01} mode, indicated by arrow **30**, FIG. **5**, to an intermediate mode, indicated by arrows **32**, FIG. **6**, and when n=4 the intermediate mode is a cross-shaped TE_{22+}. Section **2**, shown in FIG. **3**, converts the intermediate mode into n TE_{10} modes. The n-sided pyramidal structure **42** transitions the intermediate mode into n rectangular TE_{10} modes. With n=4 the pyramidal structure has four sides and a square base **44**. The apex **46** of the pyramid is located in the center of the device at approximately the intersection of sections **1** and **2**. At the apex **46** of the pyramidal structure **42** the electric field is nearly zero (on the axis) for minimal field perturbation. The outer arc-shaped boundaries, indicated at **48** in FIGS. **2** and **6**, of each arm **50** gradually transition to straight waveguide walls, indicated at **52** in FIGS. **3** and **9**, along the length of section **2**. The transition is indicated at **49**, FIG. **14**. At the position indicated by cross-section EE, FIGS. **3** and **9**, the base **44** of pyramid **42** has divided arms **50** into four spatially independent rectangular waveguides. In section **3**, FIG. **4**, the rectangular waveguides continue to separate spatially and at the position indicated by section FF in FIGS. **4** and **10**, four standard rectangular waveguides are attached. With n=8, for example, eight standard waveguides would be attached at the position indicated by section FF.

FIGS. **11–13** show detailed dimensions at selected cross sections of section **1** shown in FIG. **11**. The dimensions are given in units of free space wavelengths λ_o to allow scaling to any frequency of interest. The length 1_o of each section is at least $3\frac{1}{3}\lambda_o$. A nominal length of $3\frac{1}{3}\lambda_o$ is applied here as the basis for computing the cross-sectional dimensions. The inner diameter d indicated at **54** in FIGS. **12** and **13** of the overmoded circular end **18** of the transducer and the waveguide to be attached is chosen sufficiently small so that the higher order circular TE modes (i.e., TE_{om}, m=2,3, . . .) cannot propagate. The diameter d is large enough, however, to provide low signal distortion in the TE_{01} mode within about ±7% of the center frequency. The arms **50** at section BB, FIGS. **11** and **13**, have a dimension t indicated at **56** equivalent to the rectangular waveguides to be attached at the other end of the transducer. For the design illustrated herein, conventional approximately "half-height" waveguides are used, for example, WR284, where $t=w/2=0.37\lambda_o$ where w is the waveguide cross section length.

FIGS. **14–18** show the primary design features of section **2**. The most important design details are the dimensions of the pyramidal structure **42** and the transition of the outer walls of arms **50** from arced, indicated at **48**, FIG. **16**, to straight, indicated at **52**, FIG. **18**. The apex **46**, FIG. **15**, of pyramidal structure **42** is situated on the axis of section **2** and has dimensions of

$S_B = 0.04\lambda_o$ on each side indicated at **53**, FIG. **15**, and is rounded to reduce electric field concentration to reduce arcing. In the center of section B'B' the electric field is very small and the introduction of apex **46** will not significantly change the electric field patterns. The side dimension S of the pyramidal structure **42** increases by $0.1\lambda_o$ for each $1.0\lambda_o$ increase in length from section B'B' towards section E'E'. The parameter S is determined at an arbitrary distance l_2 from section B'B' from the following formula:

$$S = 0.1\ l_2 + 0.04 \text{ (in units of } \lambda_o\text{)},$$

for example, at S_C is calculated as follows:

$$S_C = 0.1\ l_{B40\ G} + 0.04 \text{ (in units of } \lambda_o\text{)}$$

wherein $l_{B'G}$ is indicated in FIG. **14**. Similarly, S_D, indicated at **60**, FIG. **17**, is calculated as follows:

$$S_D = 0.1\ l_{B'H} + 0.04 \text{ (in units of } \lambda_o\text{)}.$$

At section E'E', FIGS. **14** and **18**, the cross section of pyramidal structure **42** has increased to the extent that the areas of arms **50** are spatially independent whereby four "half-height" rectangular waveguides emerge, each supporting the TE_{10} mode. The sides of pyramidal structure **42** at section E'E', FIG. **18**, are equal to t, as indicated at **62**, FIG. **18**.

Between section B'B', FIG. **15**, and section GG, FIG. **16**, the cross section of pyramidal structure **42** increases without a corresponding increase in the diameter d of a circle, indicated at **64**, circumscribing arms **50**. In other words, the side of transverse dimension S of the pyramidal structure **42** gradually increases, in accordance with the above equation, in the direction from cross-section B'B' to cross-section G'G'; while the extending arms **50** remain at a constant cross-section (compare FIGS. **15** and **16**). At section GG the length w indicated at **66**, FIG. **22**, between pyramidal structure **42** and the straight line connecting the ends of the arced outer wall is $w = 0.793\lambda_o$. The dimension w is the long dimension of the "half-height" conventional waveguide for $t = 0.374\lambda_o$.

From section GG to section E'E' each arm **50** is fixed at length w from pyramidal structure **42**, therefore, as the pyramidal side length S increases the transducer cross sectional length (2w+S) correspondingly increases. Between section GG and section HH, about $0.34\lambda_o$ in length, the outer wall of each of arms **50** transitions in shape from an arc of the circumscribing circle **64** of diameter d to a straight wall as indicated at **49**, FIG. **14**. FIGS. **22-24** illustrate the details of the transition in wall shape. FIG. **22** illustrates the outer wall shape at section GG which lies $1.18\lambda_o$ from section B'B'. FIG. **24** illustrates the straight outer wall at section HH which lies $1.18\lambda_o + 0.34\lambda_o$ from section B'B'. FIG. **23** illustrates an intermediate section between section GG and section HH wherein the pyramidal side S of structure **42** is equal to $S_c + 0.17\lambda_o$ and lies $1.18\lambda_o + 0.17\lambda_o$ from section B'B'.

FIGS. **19-21** show detail of section **3**, the purpose of which is to gradually separate the rectangular waveguide arms **50** until spacing is sufficient to allow couplers to be attached for connection to conventional waveguides. The length of this section also allows damping of any evanescent modes which might arise in the transition. The variable S is no longer interpreted as the side dimension of the cross section of pyramidal structure **42** but as the separation between the inner walls of coplanar waveguides. The formula for computing S versus length l_3 from section EE is:

$$S = 0.1\ l_3 + 0.374 \text{ (in units of } \lambda_o\text{)}.$$

Therefore, the distance S_I, FIG. **20**, is calculated as:

$$S_I = 0.1\ l_{EE} + 0.374 \text{ (in units of } \lambda_o\text{)}.$$

It is noted that a standard rectangular waveguide stepped-transform match section may be required in each arm **50** of section **3** to optimally match rectangular waveguides to the transducer.

For convenience to the reader the applicable dimensions are reproduced in Table I as follows:

TABLE I

$l_o = 3\frac{1}{3}\ \lambda_o$	$S_B = 0.04\ \lambda_o$
$l_{B'G} = 1.18\ \lambda_o$	$S_C = 0.158\ \lambda_o$
$l_{GH} = 0.34\ \lambda_o$	$S_D = 0.192\ \lambda_o$
$l_{HE'} = 1.81\ \lambda_o$	$S_E = 0.374\ \lambda_o$
$l_{EE} = 1.67\ \lambda_o$	$S_I = 0.54\ \lambda_o$
$l_{EF} = 1.67\ \lambda_o$	$S_F = 0.707\ \lambda_o$
$d = 1.78\ \lambda_o$	
$w = 0.793\ \lambda_o$	
$t = 0.374\ \lambda_o$	

The above dimensions represent the best mode known at the time of filing the present patent application. While the invention has been described with reference to the accompanying drawings and associated dimensions, it is to be clearly understood that the invention is not to be limited to the particular and specific details shown herein as obvious modifications and dimensional variations may be made by those skilled in the art. The scope of the invention should only be construed within the scope of the following claims.

What we claim is:

1. A waveguide apparatus for transducing between a circular TE_{01} mode and multiple (n) rectangular TE_{10} modes comprising:

- a first waveguide means having a circular cross section at one end thereof supporting said circular TE_{01} mode and a multiple (n) arm cross section at its opposite end forming a multiplicity (n) of radially extending waveguide arm segments, each supporting an intermediate TE mode,
- a second waveguide means having a multiple (n) radially extending arm cross section along its length and being connected at one end to mate with said opposite end of said first waveguide means, the opposite end of said second waveguide means being formed as a multiplicity (n) of radially extending rectangular arms each open on one of its shorter sides facing the center of said second waveguide means,
- a pyramidal means having an apex centered within said second waveguide means adjacent to but physically disconnected from said one end of said second waveguide means and having a base centered within said second waveguide means at the opposite end of said second waveguide means, said pyramidal means having a multiplicity (n) of sides extending the length of said second waveguide means but disconnected physically from said second waveguide means except adjacent the base of said pyramidal means to close the open side of each of said multiplicity (n) of radially extending rectangu-

lar arms and complete formation of a multiplicity (n) of rectangular waveguide elements, each supporting said rectangular TE_{10} mode, and

a third waveguide means comprising a multiplicity (n) of separate rectangular waveguide members each supporting said rectangular TE_{10} mode and each having one end connected to a respective one of the waveguide elements formed by the connection of said second waveguide means and the base of said pyramidal means.

2. The waveguide transducer apparatus specified in claim **1** wherein said first waveguide means includes an equal multiplicity (n) of wall indentation means spaced equidistant about the circumference of said first waveguide means extending longitudinally in said first waveguide means and gradually increasing in depth from said one end towards said opposite end to divide said first waveguide means into said multiplicity (n) of radially extending waveguide arm segments.

3. The waveguide transducer apparatus specified in claim **2** wherein the multiplicity (n) of wall indentation means are spaced apart by 360°/n about the circumference of the circular cross section end of said first waveguide means.

4. The waveguide transducer apparatus specified in claim **3** wherein each of said wall indentation means is formed at an angle corresponding to the supplement of the angle formed by adjacent sides of said pyramidal means, whereby each of said radially extending waveguide arms extend at a right angle to a corresponding side of said pyramidal means, and

wherein the radially extending arms of said second waveguide means extend at right angles to corresponding sides of said pyramidal means along the length of said second waveguide means.

5. The waveguide transducer apparatus specified in claim **1** wherein the opposite end of each radially extending waveguide arm segment of said first waveguide means has an outer wall of arc shape and wherein each radially extending arm of said second waveguide means has an outer wall which transitions from an arc shape adjacent to its said one end corresponding to the arc shape of the outer wall of the opposite end of a respective radially extending waveguide arm segment of said first waveguide means to a straight shape at its said opposite end.

6. The waveguide transducer apparatus specified in claim **4** wherein n=4, wherein said intermediate TE mode is TE_{22+} and wherein said pyramidal means has a square base to complete formation of four rectangular waveguide elements, whereby a circular waveguide supporting a circular TE_{01} mode may be connected through said waveguide transducer apparatus to four separate rectangular waveguides each supporting a TE_{10} mode.

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